Inhomogeneous Chemical Evolution of the Galactic Halo

C. Travaglio[1,2], A. Burkert[1] and D. Galli[3]

[1]Max-Planck Institute für Astronomie, Heidelberg, Germany

[2]Dipartimento di Astronomia e Scienza dello Spazio, Firenze, Italy

[3]Osservatorio Astrofisico di Arcetri, Firenze, Italy

Abstract: In this contribution we describe the basic features of a Monte Carlo model specifically designed to follow the inhomogenous chemical evolution of the Galactic halo, taking into account the effects of local enrichment and mixing of the halo gas, and with particular emphasis on elements like Eu produced by *r*-process nucleosynthesis. We compare our results with spectroscopic data for the chemical composition of metal-poor halo stars and globular clusters like M13, M5, M92, M4, and we infer some constraints on the star formation history of the halo and the rate and mass spectrum of supernovae during the first epoch of Galaxy evolution.

1 Introduction

The results of several observational studies suggest the existence of a considerable scatter of heavy element abundances (over about 2 dex in [element/Fe]) in a large sample of low-metallicity halo stars (see e.g. Gilroy et al. 1988, Ryan & Norris 1991, Gratton & Sneden 1994, McWilliam et al. 1995b, Ryan et al. 1996, and, more recently, McWilliam 1998, Sneden et al. 1998). However, the actual nature of this scatter, and the possible influence of various effects like different calibration methods or data reduction procedures, is still controversial. If the observed scatter is *intrinsic*, one is led to consider a scenario in which the oldest halo stars were formed out of a gas of spatially inhomogeneous chemical composition. For instance, the peculiar abundances determined by Sneden et al. (1994) and McWilliam et al. (1995a) in the star CS 22892-052 (where *r*-process elements are enhanced over 40 times the solar value) strongly support this hypothesis. Moreover, the presence of *r*-process elements in low-metallicity halo stars is indicative of a prompt enrichment of the Galaxy by early generations of massive stars, as first suggested by Truran (1981).

A detailed analysis of the Galactic evolution of heavy elements from Barium to Europium has been recently performed by Travaglio et al. (1999) adopting the standard approach to the chemical evolution of the Galaxy, where stars are assumed to form from a chemically homogeneous medium at a continuos rate. As the authors stressed, this approach is able to reproduce spatially averaged values of element abundances over the Galactic age, but a more realistic model for the chemistry and dynamics of the gas is needed in order to investigate the earliest phases of halo evolution.

Studies of inhomogeneous enrichment of the Galaxy have been recently carried out by Raiteri et al. (1999), Tsujimoto et al. (1999), and McWilliam & Searle (1999). The work by Raiteri et al. (1999) is mostly concerned with the evolution of Ba, followed by means of a hydrodynamical N-body/SPH code; the work by Tsujimoto et al. (1999) is focused on the spread in Eu observed in the oldest halo

stars, explained in the context of a model of supernova-induced star formation; finally, the work by McWilliam & Searle (1999) is based on an original stochastic model for the chemical evolution of the Galaxy aimed at reproducing the observed Sr abundances.

In this contribution we present the results of a Monte-Carlo code for the chemical evolution of the Galactic halo, based on the idea of fragmentation and coalescence between interstellar gas clouds. With this approach, described below in more detail, we take into account the effect of mixing between clouds, bursts of star formation in the clouds and the consequent chemical enrichment of the gas, and the delayed mixing of supernova ejecta into the interstellar medium (hereafter ISM). In particular, we present here our results for Eu and for the age-metallicity relation in the earliest phases of the Galaxy.

2 A Stochastic Model for the Galactic Halo

The main characteristics of our chemo-dynamical model are (i) a realistic treatment of chemical inhomogeneities in the ISM due to incomplete mixing of stellar ejecta, and (ii) the occurrence of discrete episodes of star formation localized in time and space. Here we summarize briefly the parameters of our model, and we discuss the sensitivity of our results to the values adopted for these parameters.

The idea that interstellar clouds collide and grow by coalescence up to a critical mass at which they become gravitationally unstable and form stars was first suggested by Hoyle (1953) and Oort (1954). In the present work, we consider the halo composed by discrete gas clouds with initial mass in the range 10^3–10^4 $M_\odot$ and we follow their evolution for 1 Gyr, with a timestep of 10^6 yr, since our main interest is the early chemical evolution of the halo. Every 10^7 yr a cloud experiences a collision with another cloud, with a probability depending on the mass of the clouds and on their collision cross section $\sigma_{ij} \propto (M_i + M_j)^{2/3}$. In particular, considering clouds as geometrically similar particles, we define a collision probability

$$P_{ij} = \frac{M_i M_j \sigma_{ij}}{M_{\rm max}^2 \sigma_{\rm max}}, \tag{1}$$

normalized to the values of the mass $M_{\rm max}$ and cross section $\sigma_{\rm max}$ of the most massive cloud at each timestep. As a result of the process of coalescence, more massive clouds are produced at each timestep, and at a critical value of $M_{\rm cr} = 10^4$ $M_\odot$ the cloud becomes gravitationally unstable and is allowed to give birth to a cluster of stars. We assume that the probability for a star formation burst is a function of the cloud's age and has the shape of a Gaussian peaked on $t = 2 \times 10^7$ yr after the formation of the cloud. Following a star burst, a cloud is fragmented by the energetic processes that accompany star formation, and breaks up into a distribution of smaller clouds.

The mass spectrum of the stars formed in the burst is described by a Salpeter initial mass function

$$\frac{dN}{dm}(m) = Am^{-2.35}, \tag{2}$$

where m is the mass of the star and A is a normalization constant. We also assume a star formation efficiency $f = 0.03$, that is each burst converts 3% of the mass of the parent cloud M into stars. If the range of stellar mass extends from 0.1 $M_\odot$ to 120 $M_\odot$, then A can be determined by the condition

$$A \int_{0.1}^{120} m \frac{dN}{dm}(m) dm = fM, \tag{3}$$

giving

$$A \simeq 0.17 f \left(\frac{M}{M_\odot} \right). \tag{4}$$

As an example of the results of our model, we show in Fig. 1 the age-metallicity relation obtained under the assumptions described above. Since Galactic Fe is mostly produced by stars which explode as core collapse supernovae, we have adopted the Fe yields computed by Woosley & Weaver (1995), for the mass range 12–40 $M_\odot$ (model B, for $Z = 10^{-4} Z_\odot$). As no calculations for progenitors more

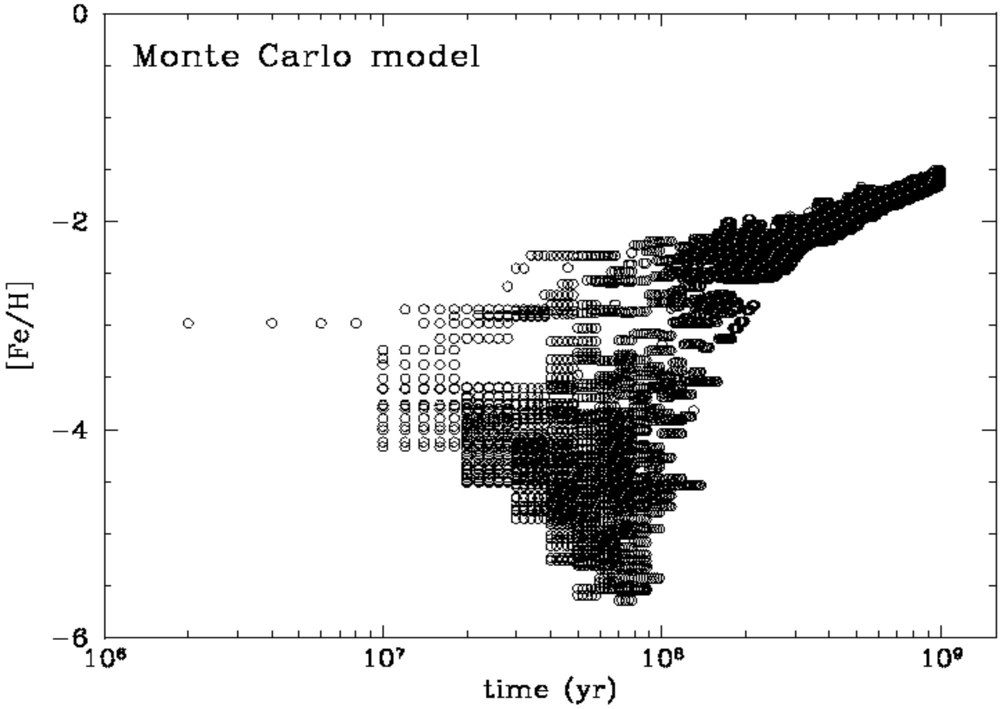

Figure 1: Age-metallicity relation obtained with our model. Open circles represent interstellar halo clouds during the first Gyr of the evolution of the Galaxy.

massive than 40 $M_\odot$ are available in Woosley & Weaver (1995), for $M > 40\ M_\odot$ we adopted the yields computed by Woosley, Langer & Weaver (1995) for a 60 $M_\odot$ and solar metallicity (model 7K). We see from Fig. 1 that the first cloud enriched in Fe up to [Fe/H] $\simeq -3$ appears at $t = 2 \times 10^6$ yr, following the first burst of star formation.

With the adopted IMF we can easily derive the number $\mathcal{N}$ of SNe per burst that contribute to this Fe enrichment in one cloud,

$$\mathcal{N} = \int_{12}^{120} \frac{dN}{dm}(m)dm \simeq 4.2f \left(\frac{M}{10^3\ M_\odot}\right). \tag{5}$$

If the cloud's mass M is in the range 10^3–10^4 $M_\odot$ and $f = 0.03$, we obtain $\mathcal{N} \simeq 1$. This result is in agreement with the point stressed by Ryan, Norris & Bessel (1991) who argued that the ejecta of a single 25 $M_\odot$ exploding in a 10^6 $M_\odot$ cloud is sufficient to enrich a cloud to [Fe/H] $= -3.8$, thus setting a lower limit on the metallicity of the second generation of stars.

From Fig.1 one can also notice that after 10^7 yr the spread in [Fe/H] increases, covering a range $-6 <$ [Fe/H] < -2. After about 10^8 yr the halo gas has had enough time to homogenize its chemical composition, and the spread in [Fe/H] is considerably reduced, converging to [Fe/H] $\simeq -1.5$.

3 The Chemical Evolution of Europium

Since the pioneering work on stellar nucleosynthesis by Burbidge et al. (1957), the origin of nuclei heavier than iron has been attributed to neutron capture processes, both *slow* (the *s*-process), and *rapid* (the *r*-process). While the *s*-process occurs mainly during hydrostatic He-burning phases of stellar evolution, the *r*-process is associated with explosive conditions in SNe. As first stressed by Truran (1981), the abundance of heavy elements in very low metal-poor stars is compatible with an

r-process origin. This point has been recently supported by new observations of low metallicity stars (see e.g. McWilliam et al. 1995b, McWilliam 1998, Sneden et al. 1998) and also by the abundance pattern determined in some peculiar stars like CS 22892-052.

Since Eu is mostly produced by r-process nucleosynthesis, the analysis of the [Eu/Fe] ratio during the early evolution of the Galaxy can provide constraints both for the inhomogeneous chemical enrichment of the halo, as well as for the astrophysical site of the r-process elements. The latter, in particular, still needs to be unambigously identified, despite the large number of recent studies (see e.g. the hydrodynamic simulations by Wheeler et al. 1998 and Freiburghaus et al. 1999), and quantitative estimates of the r-process yields are still unavailable.

Recently, the heavy elements enrichment of the Galactic halo has been analyzed in several studies, e.g. Ikuta & Arimoto (1999), Tsujimoto et al. (1999), McWilliam & Searle (1999). In all these works the r-process yields were deduced empirically from the available observational data of the most metal-poor stars. In the present work we adopted the analytical calculation of the r-process presented by Travaglio et al. (1999), which is independent on observations. These authors treated the r-process as a "primary" process originating in low-mass Type II SNe and derived the r-residuals after subtracting from the solar abundances the predicted s-fractions at $t = t_{\odot}$.

In Fig. 2 (lower panel) we show our result for [Eu/Fe] vs. [Fe/H], obtained with the model prescriptions described in Sect. 2, and using the Eu quantitative estimates (from low-mass SNe) by Travaglio et al. (1999). Our predictions are compared with the available spectroscopic data for metal-poor field stars. In the same figure, we also show, for comparison, the Eu abundances measured in several globular clusters stars. As stressed by Shetrone (1996), the [Eu/Fe] ratio follows the same trend with [Fe/H] both in globular cluster stars and in field stars. This is a good constraint for the nucleosynthesis processes that occurred in globular clusters stars. In fact, if both O and Eu originate from Type II SNe, these elements should be equally depleted in cluster and field stars, contrary to observational evidence. Therefore it is likely that the O depletion (observed in globular cluster stars but not in field stars) is not a consequence of a primordial effect, but can be attributed to nucleosynthetic processes during the evolution of these stars.

In Fig. 2 (upper panel) we also show the same age-metallicity relation shown in Fig. 1, but selecting only clouds in which there are stars able to produce Eu. This figure can provide more insight about the age at which the halo gas begins to be enriched by the r-process, as well as the metallicity range that star forming clouds enriched in Eu clouds can cover at a given epoch.

4 Discussion

The results described above concerning the enrichment in Eu of the Galactic halo make clear that in order to match the considerable spread in [Eu/Fe] observed in stars in the metallicity range $-3.5 \leq$ [Fe/H] ≤ -2.0 we need to distinguish the r-process sources (low-mass SNe with $M \simeq 10\ M_{\odot}$) with respect to Fe sources (in our model Fe is produced by stars in the mass range 12–120 $M_{\odot}$ during the first Gyr of halo evolution). We also explored the consequences of zero Fe yields for higher mass stars. This is supported by the idea that mass-loss increases with metallicity and that at the lowest metallicities the probability is higher to have even less Wolf-Rayet stars. However, since we assume that the chemical enrichment of the halo has been inhomogeneous on timescales $\geq 10^7$ yr (i.e. the lifetimes of $\sim 12\ M_{\odot}$ stars), the material ejected by the more massive stars (on shorter timescales) is considered well mixed. Consequently, to take a zero Fe yield from high mass SNe will not affect considerably the results for the inhomogeneous composition of the gas at t $\geq 10^8$ yr, when Eu production starts.

At the last timesteps, when [Fe/H] is converging to $\simeq -1.5$, the minimum value of [Eu/Fe] predicted by our model is too low compared with observations. Two points must be stressed: first, at [Fe/H] > -2 the chemical enrichment of the gas starts to be dominated by the disk, while in our simulation we followed the evolution of the halo gas only. Second, at these epochs we need to take into account other stellar sources for the chemical enrichment of the gas, i.e. Type Ia SNe for Fe, intermediate- and low-mass Asymptotic Red Giant stars for heavy elements. To obtain an early Eu enrichment (see

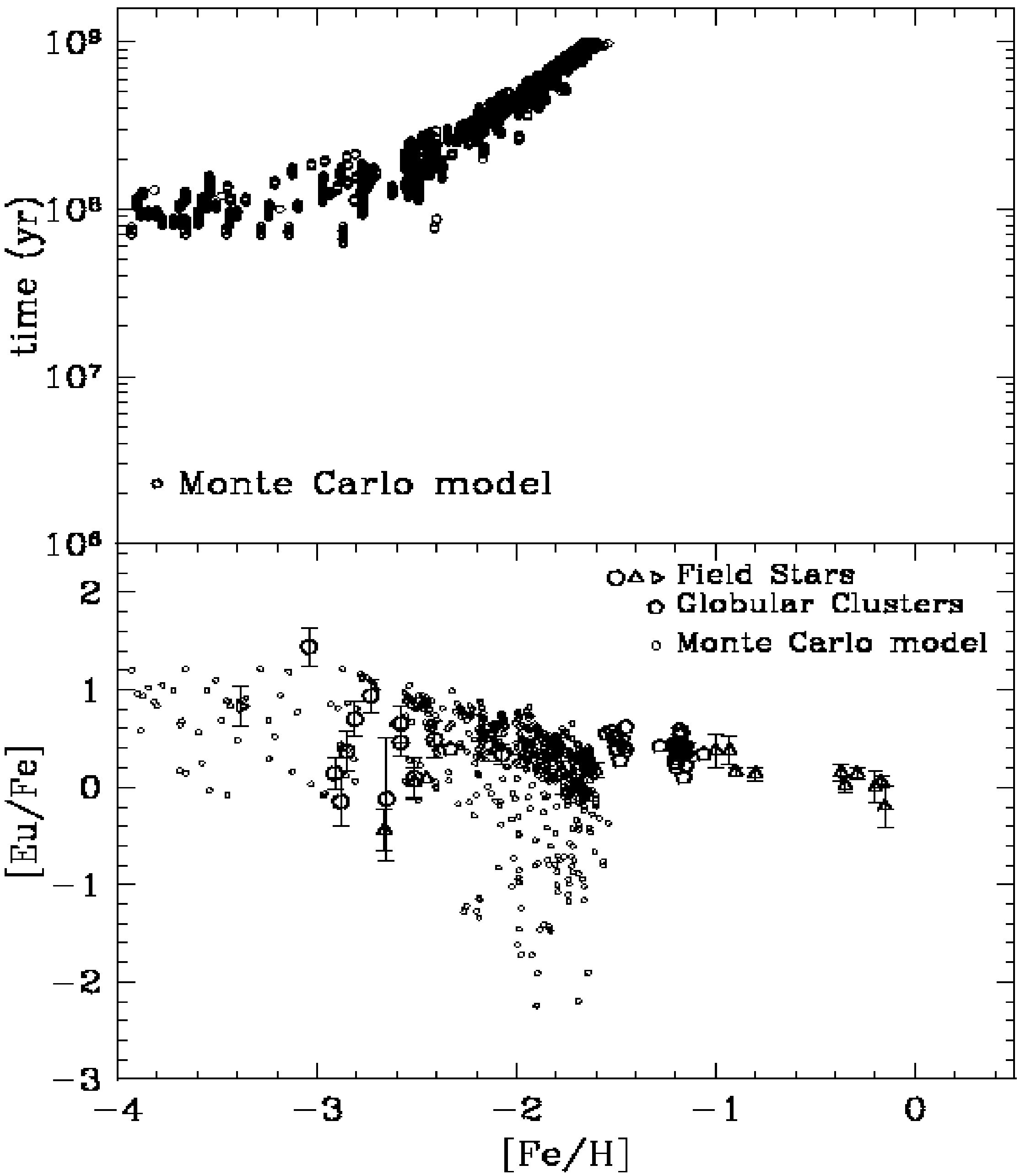

Figure 2: *Upper panel*: age-metallicity relation as in Fig. 1, but only for clouds enriched in Eu. *Lower panel*: evolution of Eu during the first Gyr of the Galaxy, according to our model (*small thin open circles*). Observational data of Eu in metal-poor stars are from: McWilliam et al. (1995) (*thick open circles*); Gratton & Sneden (1994) (*open triangles*); Norris, Ryan, & Beers (1997) (*open tilted triangles*). Data for Eu in globular clusters stars (*open pentagons*) are from Shetrone (1996) for M13, M5, M92, and from Ivans et al. (1999) for M4.

Fig. 2, upper panel) we need to reduce the time delay for the production of Eu. For this reason we explored different SNe mass ranges, adopting the corresponding Eu yields computed by Travaglio et al. (1999). For example, if we assume the case of Eu production from high-mass SNe (15–25 $M_{\odot}$), the time delay in the enrichment of Eu with respect to Fe will be too small to match the observed spread in [Eu/Fe] at $-3.5 \leq$ [Fe/H] ≤ -2.5.

Finally, we tested the sensitivity of our results to another parameter of our model, the time interval between two subsequent bursts of star formation inside clouds. The results presented here were all obtained with $t_{\rm burst} = 2 \times 10^6$ yr. For a longer time interval between bursts ($t_{\rm burst} \simeq 8 \times 10^6$ yr) the enrichment of Eu in the ISM is slower than the standard case, and the discrepancy between model results and observational data becomes particularly evident at the lowest metallicities ([Fe/H] < -3.5). A significative constraint on $t_{\rm burst}$ can be obtained by applying the same analysis presented here for Eu to elements observed at even lower metallicities ([Fe/H] $\simeq -4$), like Ba and Sr. These results will be presented in a forthcoming paper, together with a more detailed study of the sites for the production of r-process and the analysis of the consequences of the infall of gas from the halo to the disk.

References

Burbidge, E.M., Burbidge, G.R., Fowler, W.A., Hoyle, F., 1957, Rev. Mod. Phys., 29, 547

Freiburghaus, C., Rembges, J.F., Rauscher, Kolbe, E.T., Thielemann, F.K., Kratz, K.L., Pfeiffer, B., Cowan, J.J., 1999, ApJ, 516, 381

Gilroy, K.K., Sneden, C., Pilachowski, C.A., Cowan, J.J., 1988, ApJ, 327, 298

Gratton, R.G., Sneden, C., 1994, A&A, 287, 927

Hoyle, F., 1953, ApJ, 118, 513

Ikuta, C., Arimoto, N., 1999, PASJ, in press

Ivans, I.I., Sneden, C., Kraft, R.P., Suntzeff, N.B., Smith, V.V., Langer, G.E., Fulbright, J.P., 1999, astro-ph/9905370

McWilliam, A., Preston, G.W., Sneden, C., Shectman, S., 1995a, AJ, 109, 2736

McWilliam, A., Preston, G.W., Sneden, C., Searle, L., 1995b, AJ, 109, 2736

McWilliam, A., 1998, AJ, 115, 1640

McWilliam, A., Searle, L., 1999 in Galaxy Evolution: Connecting the Distant Universe with the Local Fossil Record, ed. M. Spite, (Dordrecht: Kluwer), in press

Norris, J.E., Ryan, S.G., Beers, T.C., 1997, ApJL, 489, L169

Oort, J.H., 1954, Bull. Astron. Inst. Netherlands, Vol.12, p.455

Raiteri, C.M., Villata, M., Gallino, R., Busso, M., Cravanzola, A., 1999, ApJL, 518, L91

Ryan, S.G., Norris, J.E., 1991, AJ, 471, 254

Ryan, S.G., Norris, J.E., Beers, T.C., 1996, ApJ, 471,254

Ryan, S.G., Norris, J.E., Bessel, M.S., 1991, AJ, 102, 303

Shetrone, M.D., 1996, AJ, 112, 1517

Sneden, C., Preston, G.W., McWilliam, A., Searle, L., 1994, ApJL, 431, L27

Sneden, C., Cowan, J.J., Burris, D.L., Truran, J.W., 1998, ApJ, 496, 235

Travaglio, C., Galli, D., Gallino, R., Busso, M., Ferrini, F., Straniero, O., 1999, ApJ, 521, 691

Truran, J.W., 1981, A&A, 97, 391

Tsujimoto, T., Shigeyama, T., Yoshii, Y., 1999, ApJL, 519, L63

Wheeler, J.C., Cowan, J.J., Hillebrandt, W., 1998, ApJL, 493, L101

Woosley, S.E., Langer, N., Weaver, T.A., 1995, ApJ, 448, 315

Woosley, S.E., Weaver, T.A., 1995, ApJS, 101, 181